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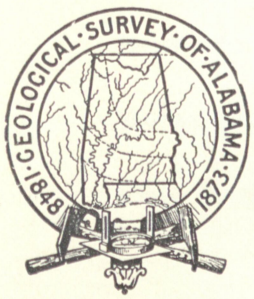
WALTER B. JONES, STATE GEOLOGIST

BULLETIN 69

Petrographic Study of the Crystalline Rocks from the Opelika Quadrangle, Alabama

by
HARLAN R. BERQUIST



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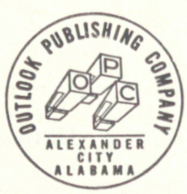

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LETTER OF TRANSMITTAL

University, Alabama
July 26, 1960

Honorable John Patterson
Governor of Alabama
Montgomery, Alabama

Sirs:

I have the honor to transmit herewith the manuscript entitled, "Petrographic Study of the Crystalline Rocks from the Opelika Quadrangle, Alabama," by Harlan R. Bergquist.

Respectfully Submitted,

Walter B. Jones

State Geologist

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INTRODUCTION and ACKNOWLEDGMENTS

The detailed study of metamorphic rocks by means of the petrographic microscope has not been as extensive as the work done on the igneous and sedimentary rocks. The difficulties attending such a study are increased somewhat by the relative scarcity of references on work of a like nature, and by the fact that similar structures and textures and even mineral relationships are sometimes found in metamorphic rocks of either igneous or sedimentary origin so that one cannot always interpret with certainty the definite origin of the rock in question. Considerable microscopic criteria have been advanced by various investigators which assist in the interpretation of the type of metamorphism which certain rocks may have undergone. Valuable as these criteria are, however, the microscopic study alone cannot always be relied upon as yielding sufficient evidence to give an adequate understanding of the history of some metamorphic rocks, but must be used as a supplement to the study of relationships seen in the field.

The writer was unable to review the crystalline rocks in the field as had been the original plans of the late Dr. George I. Adams who advanced the problem and who, together with the Alabama Geological Survey, made possible this study. The paper here submitted is a summary of a petrographic study of the crystalline rocks of the Opelika quadrangle in Alabama, the specimens being furnished by the Alabama Survey and representing material which was collected by Dr. Adams during the summer of 1931 besides other material previously collected by the state survey. About a hundred and fifteen specimens were studied and the discussion of them has been undertaken with the attempt to group them as far as possible where similarities exist or where a group is representative of a certain type. In the case of a few specimens, individual descriptions are given in order to present a clearer understanding of the mineral and textural relationships which they show. A list of each group precedes the discussion of that group. The discussion at the conclusion of the rock descriptions is aimed to correlate, where possible, the rocks as a whole with regard to the metamorphism they have undergone in the course of their development, and to interpret something of the nature of the relationships and of

the changes developed in so far as they are indicated by the structures and textures existing.

The writer wishes to thank the Geological Survey of Alabama for making possible such a study and desires to express his appreciation for the many services and suggestions rendered by the late Dr. Adams. He also wishes to thank Dr. G. W. Crickmay of the Georgia Geological Survey for allowing him to review his manuscript on the crystallines of Georgia and for the suggestions offered by Dr. Crickmay. To Dr. Frank F. Grout, Professor of Petrography and Petrology at the University of Minnesota, under whom this study was undertaken, the writer is especially greatly indebted for the supervision and considerate advice which he so kindly gave during the course of the study.

General Geology of the Crystalline Rocks

The crystalline rocks of Alabama have recently been described as to their general geology.[1] The rocks lie in the eastern part of the state (Fig. 1) in a series of folded and faulted parallel belts, forming the southwest termination of the Appalachian Region and a part of the Piedmont Upland which extends northeast through Georgia.

The rocks occur in several northeast-southwest trending belts or zones, which in the northwest part are overthrust onto unaltered Paleozoic rocks by the Blue Ridge Overthrust,[2] which is one of four large overthrusts occurring in the southern Appalachians. Along the southern edge, they are covered by overlapping Upper Cretaceous sediments. These crystalline belts are composed principally of pre-Cambrian metamorphosed sediments and igneous rocks, some of which have been locally invaded and still further altered by younger igneous rocks.

The southeast portion of the belt of crystalline rocks, lying in the Opelika quadrangle, consists largely of gneisses, schists

[1] Adams, George I., General geology of the crystallines of Alabama. Jour. of Geol. vol. XLI, 1933, pp. 159-173.

[2] Jonas, Anna I., Structure of the metamorphic belt of the southern Appalachians. Am. Jour. of Sci. vol. 24, 1932, pp. 232 & 233.

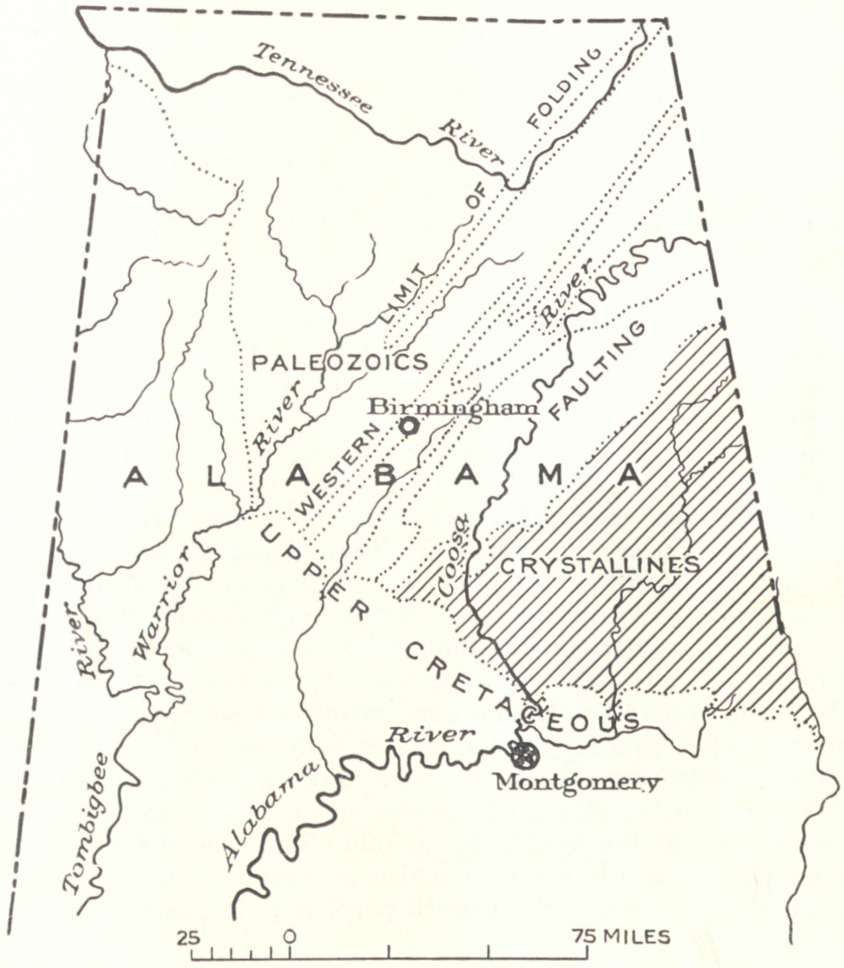

Tennessee River
FOLDING
LIMIT OF
River
PALEOZOICS
Birmingham
FAULTING
ALABAMA
WESTERN
UPPER
CRETACEOUS
CRYSTALLINES
Coosa
River
Warrior
River
Tombigbee
Alabama
River
Montgomery
25
0
75 MILES

Figure 1.

and mylonites together with minor beds of dolomite and quartzite. This area has been divided[3] into the Dadeville, Opelika, Wacoochee and Uchee belts (Fig. 2). The Dadeville lies northwest of the others and no rocks from it were studied. The rocks here studied came from the Opelika, Wacoochee and Uchee belts in Lee and Chambers counties. The equivalents of these belts extend northeast into Georgia.

The Opelika belt is five or six miles in width, extending northeast and southwest from Opelika, Alabama. It is composed of muscovite schists, a few occurrences of granite gneiss and belts of biotite gneiss lying in strike with the regional structure. Some muscovite mica prospects are found in the biotite gneiss area.

Lying to the southeast of the Opelika belt is the Wacoochee, composed of biotitic schists, two zones of quartzite (Hollis quartzites, which at Wright's Mill is intruded by porphyritic gneiss), a little dolomite adjacent to the quartzite, two distinct zones besides some minor occurrences of the banded porphyroclastic rocks (mylonites?), a zone of granite gneiss and lenses of biotite augen-gneiss. The banded mylonites, the best of which are exposed near Bleecker, vary from dense to thin banded porphyritic beds. In the northeastern part of the Wacoochee area, these rocks are cut by biotite augen-gneiss, the finer grained phase of which resembles the banded porphyry (mylonites?). Four miles south of Auburn, on the north side of Chewacla Creek (Wright's Mill and vicinity), is an area of biotite-augen gneiss bearing phenocrysts of feldspar as large as two inches in diameter. Across the creek to the south is Hollis quartzite, while in the stream the gneiss appears to be intruded between beds of the quartzite. In other localities the gneiss is finer grained and is found in schists or near the quartzites and is believed to intrude the banded porphyries in some places.

Adams describes the granite gneiss (mylonite) as being found chiefly between the two belts of banded porphyries. Near Wacoochee there are small outcrops of a grayish granite gneiss while granite mylonite occurs on the Chattahoochee River near Goat Rock dam.

[3] Adams, George I., op. cit. pp. 168-173.

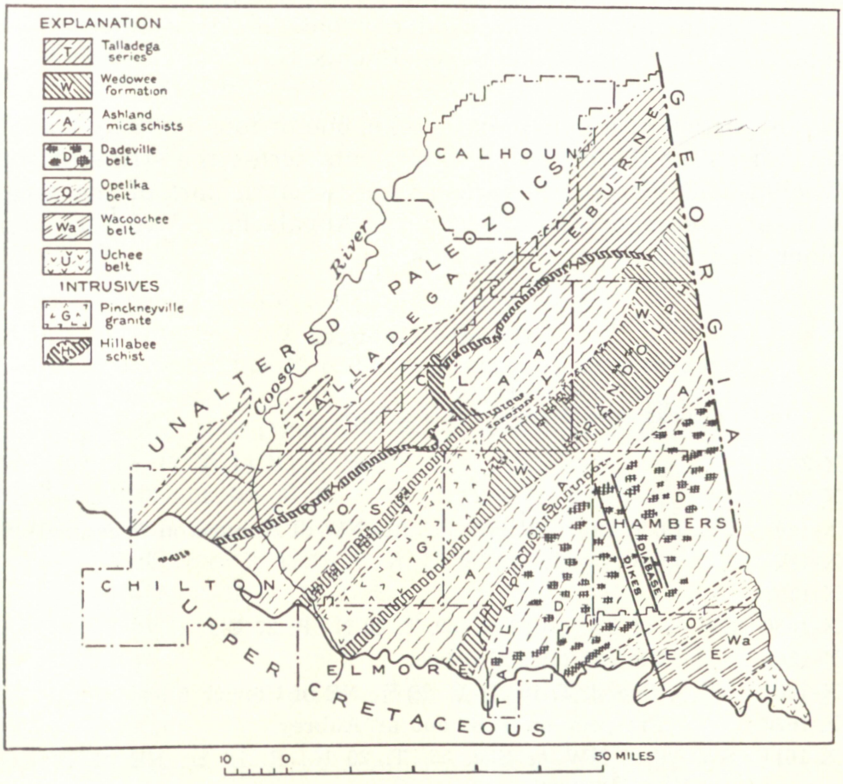

EXPLANATION
Talladega series
Wedowee formation
Ashland mica schists
Dadeville belt
Opelika belt
Wacoochee belt
Uchee belt
INTRUSIVES
Pinckneyville granite
Hillabee schist
UNALTERED PALEOZOICS
TALLADEGA
CLEBURNE
GEORGIA
CALHOUN
Coosa River
CHILTON
CHAMBERS
UPPER CRETACEOUS
50 MILES

Figure 2.

The southeasternmost belt of the crystalline rocks is that designated as the Uchee area. This zone is largely obscured by remnants of the Upper Cretaceous sediments and river terrace gravels which encroach upon it from the south. Exposures are found on Little Uchee Creek and its northern tributaries and at other localities. The rocks are largely gneisses—granite gneiss in the northwest, granite gneiss and biotite gneiss at Moffet's Mill on Uchee Creek, contorted biotite gneiss injected by granite on Whites Creek, hornblende gneiss along the Opelika-Columbus highway, and contorted hornblende gneiss injected by granite in the river bed between Phenix City and Columbus.

A portion of a long diabase dike, one of four recently traced by Adams[4] in the crystalline area, cuts across the strike of the Opelika and Wacoochee rocks in the western part of the area. It is of later age than the general Appalachian structure and older than the Upper Cretaceous.

Granite Gneisses

List of rocks considered in this group:

X-30
X-88
X-140 Sec. 19, T. 19 N., R. 26 E., 1 mile NW of Auburn on Drakes place.
X-147
X-1557
X-1560 SW ¼ of SE ¼ of Sec. 30, T. 20 N., R. 27 E.
X-1566 Clower Mica Prospect.
X-1607 NE ¼ Sec. 3, T. 19 N., R. 26 E., NE of Clower Mica
X-1620 Prospect on R.R. cut at Aubrey.
X-1611 SW ¼ of NW ¼ Sec. 36, T. 20 N., R. 26 E., NE of Clower Mica Prospect.
X-25 NW ¼ NE ¼ Sec. 19, T. 19 N., R. 26 E., near Auburn.
X-39 T. 21 N., R. 28 E.
X-42 NW ¼ NE ¼ Sec. 18, T. 19 N., R. 26 E., Lee Co.
X-46 N of SW ¼ Sec. 36, T. 19 N., R. 26 E.
X-50 NE ¼ NW ¼ Sec. 1, T. 19 N., R. 26 E., near Auburn.
X-97 NW ¼ NW ¼ Sec. 12, T. 18 N., R. 26 E., SE of Auburn.
X-126 NW ¼ SE ¼ Sec. 35, T. 18 N., R. 30 E., on Alabama

[4] Adams, George I., op. cit. p. 172.

X-129 side of river just below Bibb City dam.
X-137 W of SW ¼ of Sec. 2, T. 18 N., R. 28 E., SE of Opelika, Lee Co. (a hornblende gneiss).
X-142 T. 19 N., R. 25 E., 4 miles W of Auburn, Lee Co.
X-164 Near Tony's Mill, Lee Co.
X-166 Polridge's Mill on west Wacoochee creek, Lee Co.
X-167 T. 19 N., R. 26 E., Frazer's Mill ¾ mi. NW of Opelika.
X-197 T. 19 N., R. 29 E., 12 miles N of Columbus, ¼ mile N of Soap Hill Crossing, Lee Co.
X-354 SE of NW Sec., 21, T. 19 N., R. 25 E.
X-885 Osanippa, Lee Co.
X-895 Just S of Wacoochee Co. Bridge at Polridge's Mill, Lee Co.
X-1596 6 miles N of Columbus, Ga. on river road.
X-1597 1½ miles N of So. station on center of Ga. R.R., T. 18 N., R. 29 E.
X-1608 Sec. 29, T. 20 N., R. 28 E., Halawakee creek.
X-1613 N line of Sec. 25, T. 18 N., R. 29 E., 5 mi. E of Bleecker station on center of Ga. R.R.
X-1627 5 miles N of Columbus, Ga. on river road.
X-1630 E ½ of Sec. 7, T. 20 N. R. 28 E.
X-1631 Harris Co. line N. of Columbus, Ga. on river road.
X-1633 SW ¼ Sec. 15, T. 19 N., R. 29 E., ½ mi. E. of Wacoochee.
X-1636 5 miles N of Columbus, Ga. on river road in Ga.
X-1639 Sec. 17, T. 18 N., R. 30 E.
X-1648 W line of Sec. 31, T. 18 N., R. 29 E. on Whites creek.
X-1650 NW ¼ Sec. 30, T. 18 N., R. 29 E.
X-1652 W line Sec. 3, T. 18 N., R. 29 E. on Whites creek.
X-1653 Sec. 5, T. 19 N., R. 27 E.
X-1666 Cataula, Ga.

Description of Granite Gneisses.

The granite gneisses comprise the greatest number of the rocks examined. These came largely from the Opelika and Uchee belts with a few from the Wacoochee belt which lies between the other two. For the most part these are thoroughly recrystallized rocks, mostly of a banded and rarely of a folded nature. A few specimens show hydrothermal alteration. The texture ranges from fine grain to very coarse. Most of the gneisses are gray, though some are quite light and a few are of a pinkish color.

The microscopic examinations show that the gneisses are

composed essentially of quartz, plagioclase, orthoclase, microcline, biotite, and muscovite. These minerals, and especially the microcline, occur commonly as large crystals. As accessories, the following are present,—zircon, titanite, apatite, magnetite, garnet, pyrite, and allanite, while in one specimen there are a number of grains of tourmaline associated with magnetite. Kaolinite, epidote, zoisite, leucoxene, hematite, limonite, opal?, sericite, and chlorite occur as secondary products besides a little carbonate being present in some of the sections. Hornblende occurs in small amounts in a couple specimens and in one of these the hornblende is largely altered to biotite which forms a peculiar intergrowth about it.

Apatite occurs in some rocks as clusters of small grains (.14 mm. to .28 mm. in the longest dimension) and in others as large grains up to .67 mm. long, following the schistosity. Garnet metacrysts are developed in places, a few being as long as 1.4 mm. In a number of the rocks, the garnet shows a slight alteration to biotite and a little chlorite, the latter probably derived from the biotite.

The micaceous minerals, biotite and muscovite, occur chiefly as plates. The biotite in the gneisses of the Clower Mica Prospect in the Opelika belt, is strongly pleochroic, changing from a pale tan, to deep brown when rotated parallel to the plane of vibration. An oil test shows this biotite to have an index of 1.641 ± 4 which is higher than that usually given for biotite (1.541 to 1.638). By the use of Grout's curves for the percentages of iron oxide and magnesia in biotite,[5] the Clower Prospect biotite appears to have a composition of about 19 per cent iron oxides and 12 per cent magnesia. In this pleochroic biotite there are large haloes around zircon, a number of which are wider than the zircon itself. In certain areas the biotite has been altered to muscovite and chlorite.

For the most part the feldspar is relatively fresh looking, but there are crystals of plagioclase which have a considerable amount of kaolinite and sericite developed along the twinning bands. Patches of epidote are present on or along the edges of

[5] Grout, Frank F., Notes on biotite. Amer. Mineralogist, vol. 9, 1924, p. 163.

feldspar, but epidote also occurs as large grains. Carbonate is likewise found with the feldspar along grain contacts, cracks and twinning bands, occurring as rhombs and as irregular grains. Along twinning bands and in irregular fractures in feldspar crystals of the more altered gneisses, there is a development of an isotropic substance which appears to be opal. The same substance is present in a few altered augen-geniss (see figure 10).

When well recrystallized, the grains of the gneisses have sutured and interlocked edges, or exhibit a tendency toward elongation, whereas if not so far recrystallized they form a mosaic. Strain effects of metamorphism are seen in undulatory extinction of some quartz and bent twinning bands in a number of plagioclase crystals. Stronger cataclastic effects are shown by the development of mortar structure in several rocks, the material in the interstitial areas between the grains being composed of microbrecciated and recrystallized quartz and feldspar. Crushing effects other than mortar structure are visible in areas where larger grains, especially of quartz and feldspar, are broken into many smaller pieces with but slight displacement, a feature seen also in the augen-gneiss and in less granulated portions of the mylonites. This form of granulation in its early stages sometimes results in the slicing of a large crystal. The slices have their longest dimensions oriented parallel to the resultant fractures. (See figure 3 showing a sliced feldspar crystal, the slices having a ratio of length to width of 3:1). Leith[6] has described granulation of this type, and considers that at the time of breaking, the particles may have been arranged with their longer diameters at angles of 45° or less to the general plane of rock cleavage thus producing the sliced effect. There are textures in a few areas which more closely approach those of a mylonite. In other rocks the larger crystals show a slight rounding of the edges due to rotation during the granulation. For the most part, however, these cataclastic deformation features are not greatly developed.

Associated with areas of crushing or along grain contacts, there is commonly a development of conspicuous vermicular intergrowths of quartz and feldspar (Fig. 4). These intergrowths are much like the myrmekitic intergrowths found in some igne-

[6] Leith, C. K., Rock Cleavage, U.S.G.S. Bull. 239, pp. 37, 38 and 75.

Fig. 3. Photomicrograph of a plagioclase crystal in an augen gneiss, partly sliced into a sheared quartz-feldspar groundmass. This continued would produce mylonitic structure. Crossed nicols. X75.

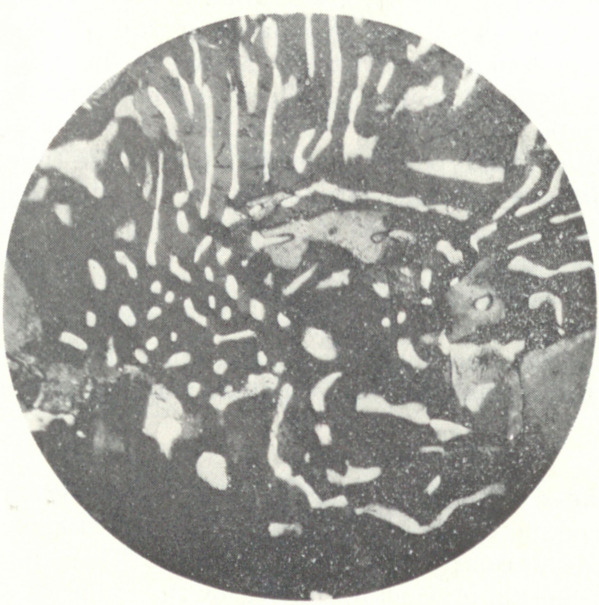


Fig. 4. Photomicrograph of symplektite—an intergrowth of quartz and plagioclase produced during metamorphism. Developed in a granite gneiss. White is quartz, dark is plagioclase. Crossed nicols. X75.

ous rocks, in which the quartz occurs as blebs, drops, and vermicular shapes within the feldspar, being produced as a deuteric effect during late stages of crystallization of a magma. Since they occur along with other metamorphic effects, in the gneisses, however, they very likely are not primary developments but must have been produced during the metamorphism. Such a texture in metamorphic rocks is known as symplektite[7] and appears to be common in a number of the different crystalline rocks of this area.

In a few of the sections there occurs a rather peculiar "bleached rim-effect" along the contact of feldspar grains, especially where microline is adjacent to plagioclase (Fig. 5). These rims are narrow and are composed of an untwinned feldspar whose index is greater than that of microcline but less than that of the twinned plagioclase (oligoclase). These rims are probably albite, formed as a result of a reaction between the oligoclase and the microcline during the recrystallization of the rock in which it is found.

The greater number of these gneisses were probably derived from ordinary granites which varied somewhat in composition in various localities. Some of the coarser ones containing the large feldspar crystals may have come from a granite porphyry. In classifying these as individual specimens, they range somewhat widely according to the minerals comprising them. Many consist largely of quartz, biotite and feldspar. In some of these plagioclase may be the dominant feldspar, in others, microcline or orthoclase. Some of the gneisses are almost free from biotite, muscovite being the predominant micaceous mineral. A few have conspicuous amounts of garnets so that they may be classed as garnetiferous biotite gneiss.

In order to have produced the present gneissose rocks, some of which are slightly "mylonitized," the original granite rocks were compressed and deformed under considerable load stresses, probably during regional metamorphism. The stresses caused the recrystallization of the rocks to a considerable extent so that a general uniformity of texture was produced. Portions of

[7] Sederholm, J. J., On synantetic minerals and related phenomena. Bull. de la Commission Geologique de Finlande, No. 48, 1916, p. 46.

Fig. 5. Photomicrograph of a feldspar rim, probably albite, between microline (dark grids) and oligoclase (gray). This occurs occasionally in the granite gneisses, due probably to a reaction between the microcline and plagioclase during metamorphism. Crossed nicols. X75.

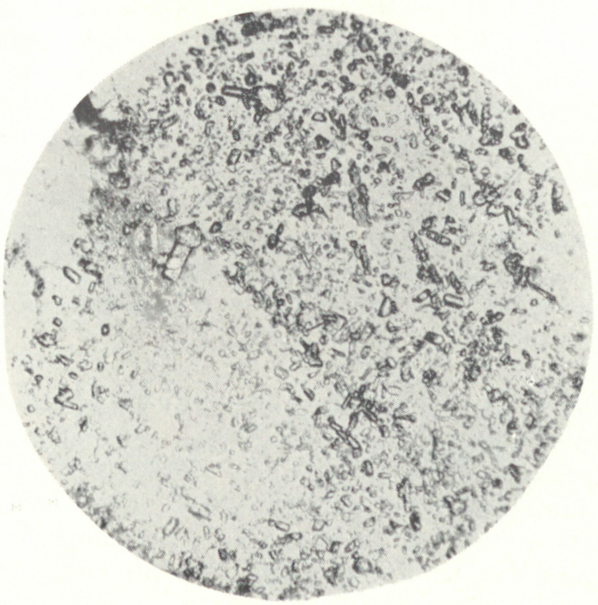


Fig. 6. Photomicrograph of automorphic crystals of epidote, zoisite, garnet, apatite, biotite, etc. in feldspar crystals. This is characteristic of the augen gneiss of Wright's Mill. Plain light. X75.

the rocks yielded to crushing without the entire recrystallization of the constituents, retaining the cataclastic effects which were produced. In a region of such ancient rocks, one which has undergone such folding and thrusting as has the Appalachian area, deformation may not have been confined entirely to one period. Part of the granulation may have occurred subsequent to the general deformation and recrystallization which produced these gneisses, for many of the cataclastic structures seem to have been produced later than the uniformly recrystallized constituents.

Augen Gneisses high in Calcium Minerals.

The following came from T. 18 N., R. 26 E., Wright's Mill, Lee county, 4 miles south of Auburn, Alabama.

X-7
X-89 (fine phase of X-7)
X-122
X-134 (fine phase of X-7)
X-146
X-160
X-161
X-171
X-207
X-212
X-217

One specimen (X-219) came from T. 20 N., R. 28 E., 1 mile south of Halawaka on the river road, Lee Co., Ala.

X-89 and X-134 are from the bank and bed of Chewacla creek above Wright's Mill.

The augen gneiss at Wright's Mill and its vicinity in the southwestern portion of the Wacoochee belt, is practically all dark and schistose, containing coarse, lenticular, light colored crystals or augen around which the dense, dark matrix bends. Lenticular crystals in some cases have their ends crushed into thin streaks. The texture of the rocks ranges from coarse to fine, with biotite forming the chief foliated constituent around the augen.

Microscopically the lenticular areas are partly of augen and

partly of flaser structure and are composed essentially of quartz, plagioclase, orthoclase, and microcline. Many of the augen apparently are the remnants of former phenocrysts for they consist of individual lenticular crystals. (Porphyroclasts of feldspar up to two inches in diameter occur in this gneiss in the field.) The muscovite and most of the biotite, together with much of the quartz and feldspar, are recrystallized. Muscovite has developed as small flakes on feldspar and along fractures in the feldspar grains.

In all of these rocks there is a characteristic abundance of calcium minerals (epidote, apatite, titanite, zoisite, and some zircon) occurring as inclusions in the feldspar and as prominant crystals scattered throughout the rock. In the latter form they are commonly of large size,— epidote, which is the most abundant of the calcium minerals, occurs in grains up to .77 mm. in length. The larger epidote grains are zoned or have centers of strongly pleochroic material. These minerals are largely aligned with the schistosity, being associated with coarse flakes of biotite or occurring in aggregates, commonly at the pinched ends of the augen. In many of the rocks of this group, the calcium minerals form very abundant and closely spaced automorphic crystals in the feldspar (Fig. 6). These are largely epidote and zoisite with minor inclusions of titanite, apatite, and garnet along with small flakes of muscovite and biotite. They lie with no regard to grain boundaries or recrystallized areas between the portions of grains, nor do they follow any orientation; rather they are scattered at random within the host mineral.

Other accessory minerals are pyrite and magnetite which occur in minor amounts in most of these gneisses. Sericite, kaolinite, hematite, limonite, chlorite, and a little carbonate are secondary constituents in addition to the apidote and zoisite described above. The kaolinite occurs as scattered dust and as heavy patches on the feldspar in some sections. The hematite and limonite are confined largely to fractures in the rock where they occur mostly as stains.

A fine-grained, sheared and recrystallized quartzbiotite groundmass forms the matrix in which the augen and flaser lie. Coarser biotite and muscovite flakes are also present in the

matrix in alignment with the schistosity. Besides the augen and flaser, there are rounded grains lying in the schistose and recrystallized matrix (Fig. 7). Some of the flaser are of recrystallized minerals (quartz and feldspar) or exhibit mortar structures (Fig. 8) or other crushing effects. At places these gneisses have a mylonitic texture in which the fragments of larger crystals grade into fine crushed material and into the sheared groundmass. A vermicular intergrowth (symplektite) of quartz and feldspar is developed in areas of crushed material, usually along contact of two or more grains of feldspar.

In one or two specimens garnet occurs as large metacrysts bearing inclusions of quartz, plagioclase, and microcline. Epidote may likewise appear as metacrysts with titanite and zircon included within them.

The presence of the high calcium content in these rocks indicates that their originals were igneous rocks which at least locally may have been somewhat more calcic than the normal granite. This fact together with the indication of former phenocrysts suggests that the rock from which they were derived was probably a granodiorite. There are, however, a few specimens from this locality which though they are augen gneiss, are of finer texture and of much lower calcium mineral content than most of the specimens. These rocks, though closely associated with the granodiorite derivatives, must have formed from rock phases which approached the normal granite in composition. One rock, described in 1895 by J. M. Clements,[8] was considered a finer grained modification of the augen gneiss which bear the abundant calcium minerals. Both rocks were believed to have been derived from intense crushing of a biotite granite. It seems more likely, however, that the original intrusive was granodiorite and only portions of it approached normal granite. It also seems that the rocks could have suffered from more than one period of metamorphism. During part of their metamorphic cycle they apparently were acted upon by dynamic stresses which developed the metacrysts and new minerals during recrystallization. Later stresses may have produced the augen and flaser structure and aligned the crystal constituents while other

[8] Ala. Geol. Surv. Bull. 5, 1896, pp. 147-150.

Fig. 7. Photomicrograph of the schistose structure of augen gneiss in which lie rounded feldspar crystals and a few grains of titanite and epidote. The dark portions are fine grained biotite and the light areas are sheared quartz. Crossed nicols. X17.

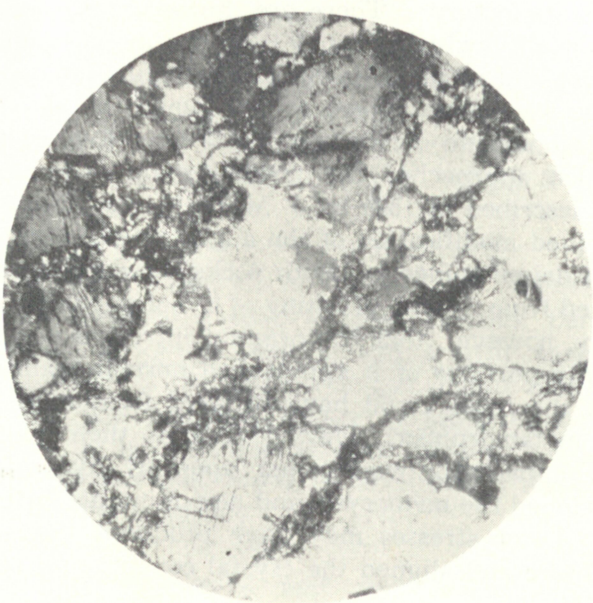


Fig. 8. Photomicrograph of mortar structure produced in an augen gneiss. Crossed nicols. X75.

areas were granulated to a microbreccia during a period of intense deformation.

Augen Gneisses Derived from Granites

X-73 T. 18 N., R. 26 E., 7 miles SE of Auburn, Lee Co.
X-149 T. 18 N., R. 26 E., 6 miles SE of Auburn, Lee Co.
X-169 T. 19 N., R. 29 E., 4 miles north of Soap Hill crossing and 12 miles north of Columbus, Lee Co.
X-194 T. 19 N., R. 27 E., 6 miles E of Auburn on Salem road.
X-213 Polridges Mill.
X-215 T. 19 N., R. 29 E., North of Mechanicsville, Lee Co.
X-358 SW ¼ SE¼ of Sec. 2, T. 18 N., R. 26 E.
X-1664 Sec. 7, T. 18 N., R. 29 E.
X-1665 Sec. 7, T. 18 N., R. 29 E.

The other augen gneisses of this set are also from the Wacoochee division, a number of them being from a belt trending northeast from a point about 7 miles southeast of Auburn, Alabama, while the others are from a few scattered localities.

These gneisses range from fine to coarse grained rocks of light to dark color with light colored crystals of quartz and feldspar forming the augen of various sizes. Microscopically the primary minerals are seen to be quartz, plagioclase, (either albite or oligoclase) orthoclase, microcline, muscovite, and biotite. Of the accessories, magnetite, pyrite, zircon, titanite, allanite, garnet, apatite, and tourmaline, the first named is the only one which occurs in every rock though two or more of the others are always present also. Epidote, zoisite, kaolinite, sericite, opal, hematite, limonite, leucoxene, and a little carbonate are the secondary minerals. Of these, epidote is the most commonly present, occurring in amounts that range from an almost negligible quantity up to 15 per cent.

The schistose groundmass which is composed of fine flakes of biotite and muscovite and needles of sericite together with sheared quartz and feldspar, is foliated around the augen and flaser structure developed in these rocks, and around scattered crystals of quartz and feldspar. The quartz is mostly strained and crushed, and shearing has rounded some of the feldspar

crystals or has reduced them to residual cores in the recrystallized groundmass (Fig. 7). A symplektite intergrowth of quartz and feldspar has replaced the edges and adjacent areas of some lenticular feldspar grains. In several sections, the grains of felsic minerals are partially broken up and lie in a fine-grained, quartzose groundmass.

Crushing has been especially intense at certain places, for the broken constitutents grade into a mylonitic texture and ultimately into the fine grained groundmass. In these areas of intense granulation in thin sections, there are narrow bands which are isotropic under crossed nicols. Apparently these bands are felsic material which was partially fused to a vitreous material by the heat developed during the cataclastic deformation acting on the rock.

Much of the epidote of these rocks is zoned or contains centers of zoisite. Commonly it forms granular aggregates on the feldspar, and at other places the crystals are elongated with the schistosity developed in the groundmass.

Inclusions of quartz and tourmaline and small flakes of biotite may occur in the feldspar. Small grains of microcline lying in more or less parallel arrangement, form an intergrowth with oligoclase in one specimen. Zircon is present as grains and as inclusions, with distinct haloes, in biotite. Scattered large and numerous small grains of tourmaline are abundant in one of these rocks. The smaller grains of this mineral are commonly associated with magnetite.

Garnet is abundant in a number of these gneisses. It is usually fractured and crushed and may have biotite and a little chlorite developed around it and in the fractures much as in the garnet of certain basic and granite gneisses (Fig. 9).

A few of these rocks show considerable alteration to kaolinite, sericite, and iron oxides, the latter in places being very abundant. Several of the sections show the feldspar altered or replaced along cracks by a secondary mineral which appears to be opal (Fig. 10).

Crushing without much recrystallization constituted the

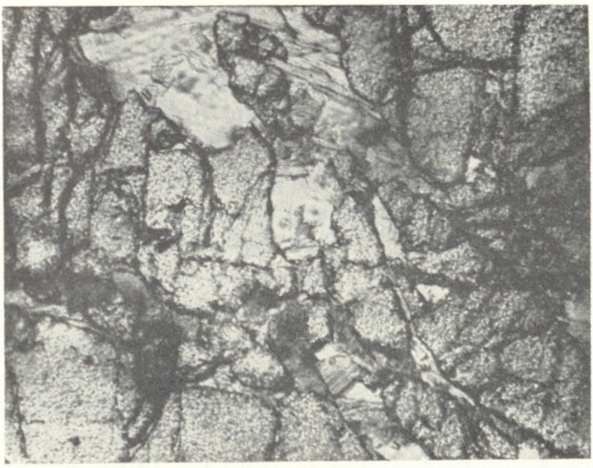


Fig. 9. Photomicrograph of garnet altering to biotite along fractures. (Biotite in some cases is especially abundant around portions of the garnet and extends into it. Such alterations may indicate slight retrogression during metamorphism.) From a granite gneiss. Crossed nicols. X75.

Fig. 10. Photomicrograph of an altered augen gneiss showing a crystal of plagioclase, altered apparently along fractures by an isotropic substance which appears to be opal. The lower right portion of the grain is broken away. The groundmass around the crystal is fine biotite, quartz, and feldspar. Crossed nicols. X75.

major change suffered by these rocks during metamorphism. Epidote, zoisite, apatite, titanite, and garnet indicate that these rocks were formed under dynamic stresses much as in the augen gneisses of Wright's Mill, though the original rock must have been more acid than at that area. The crushing effects are typical of deformation at shallow depths so that there is a possibility that the rocks may have undergone metamorphism more than once. The effects of shallow zone metamorphism superimposed on the deeper recrystallization are in evidence in the presence of augen, flaser, and mortar structure and the other granulation effects. The alteration of fractured garnet to biotite and chlorite also suggests a retrogressive reaction, a deep zone mineral altering to mica indicating a changed environment.

The low calcium mineral content of these augen gneisses indicates that their originals were more acid than those of Wright's Mill and vicinity. The originals from which these were derived were granitic in character and probably porphyritic as well, for many of the augen appear to have been former phenocrysts. They were probably originally granites and porphyritic granite.

Granite Mylonites

X-26 Sec. 29, T. 18 N., R. 28 E., North bank of Uchee creek at McKinnon's Mill.
X-101 Uchee creek below mill.
X-102 Uchee creek below mill.
X-108 Uchee creek not far above Freeman's covered bridge.
X-193 Sec. 30, T. 18 N., R. 28 E.
X-1633 SW ¼ Sec. 15, T. 19 N., R. 29 E., ½ mi. E. of Wacoochee.
X-1644 Sec. 1, T. 19 N., R. 29 E., Bartletts dam on Chattahoochee river.
X-1645 Sec. 36, T. 18 N., R. 28 E., south of center.
X-1646 Sec. 16, T. 18 N., R. 28 E.
X-1647 Sec. 16, T. 18 N., R. 28 E.
X-1651 Sec. 16, T. 18 N., R. 28 E.
X-1659 Sec. 32, T. 19 N., R. 26 E., Center. 1 mi. SE of Auburn.

The term mylonite is used to imply a process whereby a rock has been milled or rolled out so that it is entirely microbrecciated. This extreme granulation takes place under conditions in which pressure and temperature are such that the in-

dividual grains are not simply crushed into a gouge as along a fault plane, but are more or less fused together during the mashing. Some neomineralization may occur during the microgranulation.

The rocks considered as mylonites came chiefly from the southeast portion of the Wacoochee belt along Sturkie creek, section 16, T. 18 N., R. 28 E. and from near McKinnon's Mill on Uchee creek in sections 28 and 29, T. 18 N., R. 28 E. where the Cretaceous sediments overlap the crystalline rocks at that point. A few other mylonites occur in scattered localities.

In general, these rocks are light colored, fine-grained, and streaked with dark constituents. Under the microscope they are seen to be composed essentially of crushed and broken grains of quartz, plagioclase, orthoclase, microcline, and less commonly hornblende, with biotite and muscovite as small recrystallized grains and laths in streaks or a matrix for the quartz and feldspar crystals. (Figures 11 and 12 show the textures of two of these mylonites.) Some recrystallization has occurred, but for the most part this is subordinate to the cataclastic structure. A little symplektite intergrowth is developed along feldspar in the crushed areas. Coarser phases show remnants of larger grains that are partly broken up with only partial displacement of the pieces.

The accessory minerals are magnetite, titanite, apatite, zircon, pyrite, allanite, and garnet, with secondary epidote, zoisite, kaolinite, sericite, chlorite, and limonite. The accessory and secondary minerals are not abundant, some rocks containing hardly any other than a little epidote and kaolinite.

There are textural differences in these rocks which indicate differences in the degree of cataclastic deformation affecting them. The specimen from Bartlett's dam is coarser than the rest but shows a gradation from large broken crystals only slightly displaced, to areas entirely crushed with some recrystallization of quartz. Those from the vicinity of McKinnon's Mill tend to be somewhat gneissic in character, containing small quartz and feldspar lenses in streaked, crushed, and somewhat recrystallized areas. Other specimens of the same general locality likewise show much crushing of constituents but a greater amount of recrystallization and more gneissic texture.

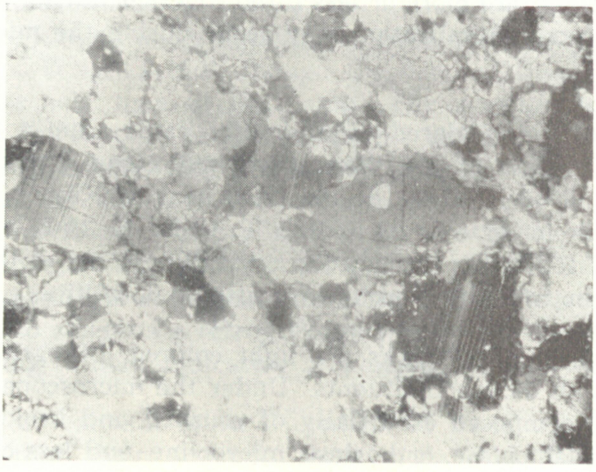


Fig. 11. Photomicrograph of mylonitic texture showing grains of quartz and feldspar broken and crushed into a sheared quartz and feldspar groundmass. Crossed nicols. X55.

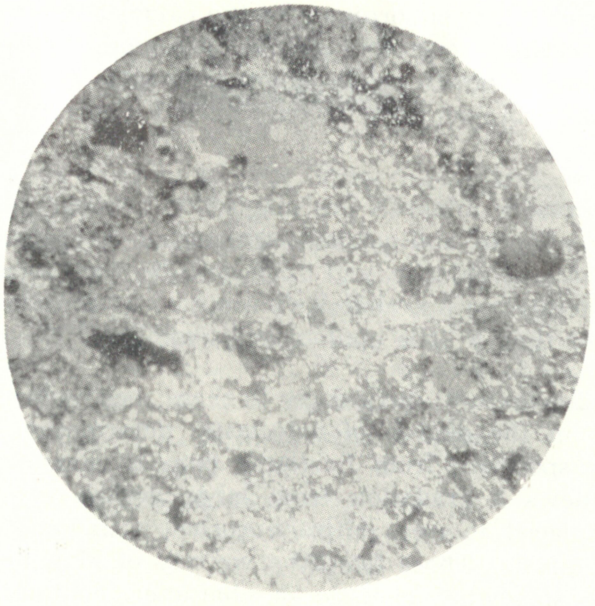


Fig. 12. Photomicrograph of mylonite structure showing constituents largely crushed except for one feldspar crystal in upper part. Crossed nicols. X17.

A cataclastic rock which shows a considerable development of recrystallized minerals that are oriented with their longer dimensions more or less parallel, has been termed mylonite gneiss by Quensel.[9] In such a rock the quartz and dark constituents are the minerals which are recrystallized,—the feldspar retaining its granulated structure. Granulation forms small particles which are subject to considerable strain, presenting conditions favorable to recrystallization. Quartz being a brittle mineral, is more easily granulated than feldspar, so that the resultant finer subdivision is more susceptible to recrystallization than is the less broken feldspar. Mica likewise recrystallizes sooner than feldspar, so that when conditions have been favorable to recrystallization in a cataclastic rock, the micaceous minerals and quartz may be found oriented in the granulated feldspar. This apparently has occurred in the mylonites at McKinnon's Mill, for although cataclastic effects are dominant, partial recrystallization makes them resemble a mylonite gneiss.

Granulation in the mylonites has not destroyed minerals to the extent that the original rocks cannot be recognized. The felsic components suggest the original were granites, which by being subjected to stresses along zones of differential movement, were crushed without being disintegrated.

Possible Mylonites and Associated Banded Porphyries

Possible mylonites:

X-1586 Sec. 5, T. 18 N., R. 29 E. Center?
X-1587 Sec. 5, T. 18 N., R. 29 E. Center?
X-1588 SW ¼ of SE ¼ Sec. 25, T. 19 N., R. 29 E. N. slope of Soapstone creek.
X-1589 (same location as for X-1588)
X-1592 Piny Grove Church, Georgia.
X-1660 Sec. 12, T. 19 N., R. 27 E. Center.
X-1661 NW ¼ Sec. 28, T. 20 N., R. 29 E. At Jester.

Banded porphyries:

X-1584 NW ¼ of NW ¼ Sec. 8, T. 19 N., R. 28 E.
X-1585 (same as for X-1584)
X-1591 SE ¼ of SW ¼ Sec. 16, T. 19 N., R. 29 E.

[9] Quensel, Percy., Bull. of the Geol. Inst. of Univ. of Upsala, vol. XV, 1916, pp. 99 & 101.

There are several rocks of this collection which from petrographic examination alone it is difficult to definitely determine whether they were derived from igneous or from sedimentary rocks. Some rocks of this nature are associated with a banded porphyry of definite igneous origin,—a fine-grained rock, foliated and banded with lenticular crystals of quartz and feldspar lying in more or less parallel streaks. The specimens which are of the rocks associated with the porphyry, range from a light gray, somewhat slaty rock with bands giving a laminated appearance and containing small lenticular crystals (quartz and feldspar) to very dense, dark rocks with similar rounded feldspar and quartz crystals.

From their field relationships, Adams (personal communication) believed a gradation could be traced from these rocks to granite gneiss, some of which lies between two parallel flanking belts of the banded porphyries (mylonites?). Crickmay[10] has likewise found several occurrences of rocks which are analogous to these and has traced a relationship between them and igneous gneisses. On the other hand, the association of known sedimentary rocks with igneous rocks in the area lends support to the possibility of a sedimentary origin, which appears to be suggestive from some of the thin sections. A few representative specimens of the dense phase are described below in detail to indicate the type of textural and mineral relationships found.

Characteristic Specimens of Possible Mylonites.

X-1587 (Sec. 5, T. 18 N., R. 29 E. Center?)

This specimen was collected by Dr. Adams near Bleecker Station in Alabama and represents the dense phase of the porphyritic rock at that locality. It is very dense, dark gray, and of uniform texture, which under the microscope appears to be composed of irregular and angular fragments of rock held together much like a breccia. A number of these angular pieces

[10] Crickmay, G. W., The occurrence of mylonites in the crystalline rocks of Georgia. Manuscript (unpublished).

appear to have a slaty texture and are of different sizes, often lying close together, but all erratically scattered and at all angles to each other. In certain of the fragments, sericite and fine grained quartz lie in parallel formation together with small round and lenticular quartz grains. Some few rock fragments are entirely of angular quartz granules or fine grained aggregates of quartz, while others contain besides these, a little orthoclase, apatite, zircon, and allanite. The interstitial material is of about the same nature as the fragments, but has not as much sericite. There is some magnetite in the matrix and traces of limonite, kaolin and leucoxene.

Microscopically this rock differs from the other dense rocks in being less sericitized and in having fragments containing the small round and lenticular quartzes. In the angularity of the fragments, the rock resembles a tuff, but the mineral and textural relationships appear more like those of a slate. Possibly this was originally an igneous rock which was crushed and granulated until it became dense and felsite-like. It may have been later subjected to stresses that caused brecciation, the fragments being cemented by granulated material from the rock itself.

X-1588 (SW ¼ of SE ¼ Sec. 25, T. 19 N., R. 29 E. North slope of Soapstone creek).

This is a uniformly fine-grained, dark, iron-stained rock with rounded and lenticular light colored crystals scattered throughout.

The thin section discloses that the groundmass is composed of fine-grained quartz and abundant sericite in which are different sized grains of quartz, orthoclase, and plagioclase of rounded, lenticular, and elongate shapes. Most of these grains have suffered no peripheral granulation that is apparent in the present state. Some grains have been partially, and a few almost completely, internally granulated, but the grain boundaries are still intact and show no development of augen. A symplektite intergrowth of feldspar and quartz works in from the borders of two of the larger orthoclase crystals.

Sericite is abundant, especially immediately surrounding the larger quartz and feldspar grains. Around the larger felsic

grains there are also commonly irregular rings of a quartzose material (Fig. 13). These were either formed by a segregation of material granulated from the crystals they surround or are the result of deposition of silica from solution.

Magnetite grains are scattered throughout the fine grained groundmass. Muscovite, apatite, zircon, garnet, and allanite are also present as accessories. The apatite is usually of large size and somewhat fractured. Zircon occurs both in the groundmass and in the plagioclase grains.

Such a structure as above described may be interpreted as the result of intense crushing of an igneous rock in which most constituents were granulated to a microbreccia while the edges of former phenocrysts were rounded when the material around them was intensely granulated. Some fusion may have occurred along the grain edges aiding in the rounding. On the other hand, the rock may have been a sediment, the felsic grains rounded by transportation and then deposited with sandy and argillaceous material which was later compressed into the present rock. The accessory minerals (especially allanite) are, however, characteristic of igneous rocks and the zircon is found both in the plagioclase and in the groundmass suggesting that it was formed within its present matrix.

X-1592 (From Piny Grove Church, Georgia).

The rock is very dense, dark, and slightly slaty with rounded grains of feldspar and quartz of different sizes. These grains are irregularly scattered through the rock, some portions being relatively free of them while other areas contain them in abundant numbers. Under the microscope it shows a dense groundmass of fine grains of quartz, biotite, and sericite, with numerous small, various-shaped grains of quartz and feldspar and a number of scattered larger grains of rounded and lenticular shape, the latter ranging in their longest dimensional measurement from .014 mm. to .126 mm. The feldspar grains include both orthoclase and silicic plagioclase. Rounded felsic grains are usually without much evidence of granulation.

Pyrite and secondary clinozoisite are abundant in streaks of more or less parallel arrangement throughout the rock. Other

Fig. 13. Photomicrograph of a dense rock (possible mylonite) showing rounded quartz and feldspar grains in a sericitic groundmass. The streaks in the lower portion of the picture are of fine quartzose material which may have been formed by solution or by the crushing of quartz grains. Sericite surrounds the rounded felsic grains, but is seen only under crossed nicols. Plain light. X17.

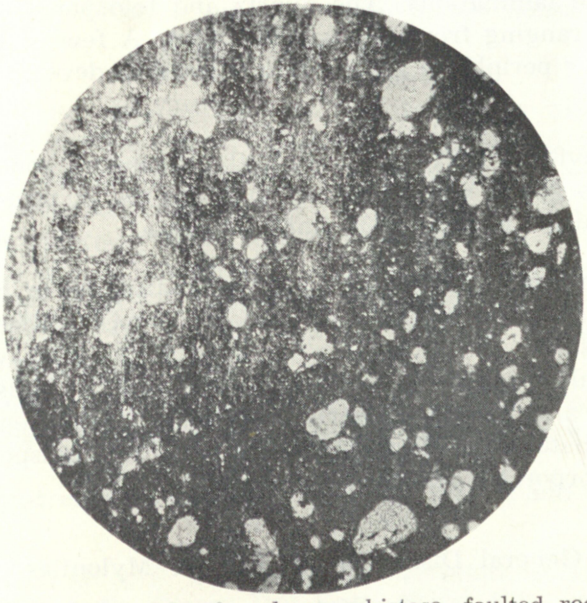


Fig. 14. Photomicrograph of a dense schistose, faulted rock showing rounded grains of quartz and feldspar in a fine-grained sericitic groundmass. A slight offset cuts the grains. This structure may have been produced by prolonged crushing of rocks of the augen gneiss type, but also suggests a possible sedimentary origin. Plain light. X17.

accessories in minor amounts are garnet, biotite, muscovite, magnetite, apatite, zircon, and titanite.

The rock is supposedly a dense phase of the gray banded porphyries and if so, it is a crushed igneous rock, but the same doubt as to its origin may arise as for that last described. In texture and appearance it is much like many tillites but no rocks of this origin have been reported from the region.

X-1660 (Sec. 12, T. 19 N., R. 27 E. Center).

This is a light gray, fine-grained, laminated rock bearing small lenticular crystals of a light colored mineral. In thin section it appears to be composed of alternating bands of different thickness, these being either entirely of sericite or are of fine-grained quartz with sericite and granules of both feldspar and quartz. These bands or laminae occur in the same manner as the alternating dark and light bands do in the hand specimen. Usually the sericite bands are narrow, but one band is wide and free from the quartz and feldspar granules found elsewhere.

The lenticular granules of felsitic material lie oriented with the sericite laminations. The quartz and feldspar grains occur in shapes ranging from angular to round. A few of the larger grains show peripheral granulation or tend to develop an augen structure.

Muscovite, a little zircon (usually somewhat rounded) and one or two grains resembling allanite, are the accessories. Leucoxene and limonite occur in small amounts.

The 'bedded and laminated' effect noticeable in both hand specimen and thin section may be only a local phase and not continuous over the entire area of the rock. It may have formed as the result of intensive granulation, the sericite bands developing by the alteration of pulverized feldspar, or representing original clay material which formed the matrix for transported sand grains incorporated within them.

General Discussion of Possible Mylonites.

These dense rocks in general contain roughly 70 to 80 per cent of sericite and fine grained quartz, with rounded or angu-

lar feldspar and quartz crystals comprising the greater portion of the remaining constitutents. Most of the accessory and alteration products mentioned in the above descriptions are found in each specimen. In a few, magnetite or graphite is abundant throughout the groundmass. None of the opaque mineral adhered to a magnet inserted in pulverized material from a couple of the specimens.

Two specimens exhibited faulting and joint planes in both hand specimens and thin sections. Along some of these 'faults' and around a few of the larger grains in one of the rocks, is a brown staining or mineral which has in it aggregates of small spherulites, each showing a prominent dark cross under crossed nicols. These spherulitic structures are probably the product of deposition of silica from solution with an iron stain to make them conspicuous. No evidence could be found that they are present in other parts of the groundmass, but disclosed only by the staining. Such a feature if it occurred would suggest the spherulites found in the groundmass of flinty crush rocks of the Vredefort region, where intense crushing has fused the pulverized material which on slow cooling formed spherulites.[11] No real evidences of fusion are noticeable in the dense Alabama rocks.

The presence of allanite in a rock is usually taken as an indication of igneous origin. This mineral occurs in several of the dense rocks and is a common accessory of foliated rocks of the locality. Becke[12] studied the phyllites of the High Tauern Alps of the Austrian Tyrol and noted rocks which closely resembled the normal phyllites in mineral and textural relationships, but in places contained orthite (variety of allanite), a mineral absent in the normal phyllites. Orthite, however, is a characteristic mineral of the old gneisses of the region, so Becke concluded that the rocks resembling phyllites were really gneisses which had undergone retrogressive metamorphism.

The occurrence of allanite in both the foliated and the dense

[11] Hall, A. L. & G. A. F. Molengraaff, The Vredefort Mt. land in the So. Transval & No. Orange Free State. Shaler Mem. series, 1925. pp. 93-114.

[12] Becke, F., Uber Diaphthorite. Tschermak's Min. und Pet. Mittheilungen, 28, 1909, pp. 369-375.

rocks of Alabama may indicate that the latter rocks were derived from the associated igneous gneisses. These dense rocks and their associates lie slightly to the west of the granite mylonites in the area of the Pine Mountain overthrust. The deformation which produced the granite mylonites could have been more intense along the western edge of the folding so that rocks along certain zones were crushed to a greater extent than elsewhere. An intensive milling can granulate rock constituents to so great a degree of fineness that only remnants of the original crystals remain. Such rocks are known as hartschiefer when characterized by a thinly banded structure and ultramylonites when of a felsite-like or chert-like appearance. The dense rocks in the Pine Mountain overthrust resemble certain of the hartschiefer and ultramylonites described by various investigators.

Banded Porphyries Associated with Possible Mylonites.

The banded and foliated rocks which field relationships indicate are a possible coarse phase of the dense rocks, definitely appear to have igneous originals. A blastoporphyritic texture is seen under the microscope, quartz, orthoclase, microcline, and silicic plagioclase forming the porphyroclasts which are of a rounded and lenticular shape, lying in a sheared quartz-feldspar-biotite matrix. Flaser structure has been developed and a general orientation of lenticular crystals with the direction of schistosity, is present. Muscovite occurs as small flakes, and as large bent blades which curve around the larger feldspar and quartz grains. A considerable amount of sericite has been developed along smeared areas of the matrix. A little vermicular quartz-feldspar intergrowth occupies the peripheral areas of a few of the larger feldspar crystals.

The accessories, garnet, zircon, apatite, titanite, and allanite are conspicuously of large size in two of the specimens, and like the primary minerals, are somewhat rounded and aligned with the schistosity. The apatite is usually fractured. Magnetite is disseminated in small grains, and leucoxene indicates the former presence of ilmenite. Epidote occurs in only one specimen.

The flaser, rounded prophyroclasts, bent crystals, peripheral granulation of crystals and symplektitic intergrowths indicate the original rock was deformed at relatively shallow depths without much recrystallization by heat. The banded appearance and textural relationships suggest the rock formed from a rhyolite porphyry, but large accessory minerals are usually found in a rock of coarser texture, as in a granite.

Rocks Similar to Possible Mylonites.

X-873 2 to 3 miles NE of Mott's Mill, Lee County.
X-888 2 to 3 miles NE of Mott's Mill, Lee County.
X-893 2 to 3 miles NE of Mott's Mill, Lee County.

Three specimens collected years ago by the Alabama Survey, lack data concerning their exact location. They are very similar to the dense rocks described above, apparently having been formed in the same manner. The rocks are dense and dark, but show a little schistosity which envelopes numerous minute, light colored lenticular crystals. The coarsest grained of the specimens, has streaks or narrow bands of a cherty material which are clearly visible with the aid of a hand lens. The rocks are cut by many small faults.

Under the microscope the groundmass shows fine-grained quartz and sericite (with a minor amount of fine biotite and muscovite flakes) in which are scattered the small lenticular and rounded quartz and feldspar (plagioclase, orthoclase, and microcline) crystals (Fig. 14) in partial alignment with the schistosity. Numerous cross faults and fractures offset the groundmass and crystals, and in some portions intersect so that the impression is created at first that the rock is composed of fragments. These fractures are filled at places by quartzose material or by iron oxide.

In addition to the lenticular felsic crystals, there are small oval garnets scattered in many parts of the groundmass. These are slightly fractured and some are partly surrounded by limonite with small biotite flakes developed in the fractures in a few. Finely disseminated magnetite, a small amount of allanite, granular aggregates of epidote and an occasional zircon crystal, complete the accessory minerals. Sericite occurs in the ground-

mass of all three specimens, but in one, which also contains a little opal, lenticular patches indicate the alteration of entire grains of feldspar to sericite.

In their microscopic structures, these rocks resemble the dense phase (mylonites?) of the banded porphyries described above, though in these latter rocks the quartz and feldspar crystals are larger (compare figs. 13 & 14). Like the other dense rocks, it is difficult to definitely ascertain the origin from microscopic study alone. A sedimentary formation is suggested by the nature of the groundmass and the small felsic grains. The oval-shaped garnets may have been produced during transportation by water, but their fractured appearance and partial alteration to biotite are like those of the garnets in the granite gneisses. Besides this, there is the allanite which is considered a criteria of igneous rocks. There is then a possibility of their derivation by the intense crushing of an igneous rock of a porphyritic nature. The phenocrysts and garnets, being more resistant than the groundmass, could have become 'worn' and rounded as the smaller grains of the groundmass were reduced to a microbreccia, acting much as an abrasive on the larger crystals.

Another rock (X-214) from Mott's Mill is quite different from the three just described above. It is a fine-grained, dark gray, schistose rock with wide bands of light colored coarser material. The thin section shows a portion of each band. The light colored area is mainly large fractured crystals of feldspar (plagioclase and orthoclase) and quartz with a quartzose filling around them. This zone grades into one of various-sized feldspar and quartz grains around which a biotite and quartzose groundmass bends. Accessory minerals are small grains of pyrite, magnetite, garnet, minute needles of apatite and a little allanite. A little epidote, streaks of limonite, kaolin dust on some of the feldspar and small flakes of chlorite, compose the alteration products. The textural and mineral relationships of the rock indicate a graywacke with lit-par-lit injection, the rock having been subjected to some relatively low temperature metamorphism.

Rocks Strongly Suggesting Sedimentary Origin.

X-886 12 miles north of Columbus, Ga. on Soap creek, Lee Co. Unnumbered specimen—From Soapstone creek.

The second of these specimens closely resembles the Carboniferous shales and is of a soft, crumbly nature. It is light colored, very fine-grained and of a banded appearance. Microscopically it is almost entirely of sericite and fine-grained quartz, resembling a slate.

The specimen from Soap Creek is likewise fine-grained and slaty. It is of a gray color with iron stains on the surface. Under the microscope it shows microcrystalline quartz and a little sericite, muscovite, and biotite, with a few scattered grains of quartz in the groundmass, not unlike many slates. A few small grains of garnet, a little zircon, disseminated magnetite, and a grain of epidote with an allanite (?) center, comprise the minor accessory constituents. A little kaolinite and a light tan isotropic mineral (hisingerite?) also occur, the latter chiefly as a stain.

These two specimens so closely resemble known sedimentary rocks that their origin may be considered settled. It is unlikely that rocks such as these could have been crushed and granulated from the gneissic rocks, for even the ultimate end product of intense mylonitization would hardly be so slaty.

Basic Rocks.

Diorite and quartz-diorite gneisses:

X-15 NW ¼ Sec. 29, T. 20 N., R. 28 E.

X-24 W part of Sec. 32, T. 19 N., R. 28 E.

X-82 SW ¼ SE ¼ Sec. 2, T. 18 N., R. 26 E.

X-218 T. 18 N., R. 29 E. (7 or 8 mi. N. of Columbus, Georgia in Lee county, Alabama).

X-1593 In river at Phenix, Ala., opposite Columbus, Ga.

X-1594 In river at Phenix, Ala., opposite Columbus, Ga. (below upper bridge).

Hornblende gneiss:

X-137 W of SW ¼ of Sec. 2, T. 18 N., R. 28 E. SE of Opelika, Lee county, Alabama.

Hornblende schist:

X-887 On river road between Soap creek and Wacoochee, 13 miles north of Columbus, Georgia.

Diorite and Quartz-Diorite Gneisses.

A few dark gray basic gneisses from scattered localities were also studied petrographically. These range in texture from fine to medium and even coarse grained rocks, and are schistose to somewhat granitoid in the hand specimen. The minerals are quartz, feldspar, hornblende and biotite, the latter being very coarse in one or two specimens.

Under the microscope most of them are very schistose, while only one shows augen and flaser structure. Hornblende, which is the most abundant of the ferromagnesium minerals, ranges in estimated percentages from 5 per cent in a rock containing considerable plagioclase and quartz, to about 50 per cent. Some hornblende is coarse, the grains resembling metacrysts and at places it is partially altered to a mineral that appears to be pyroxene. A little biotite has also formed from the hornblende.

The feldspar, which is chiefly plagioclase (a little microcline and orthoclase occur also) ranges from 5 per cent to 50 per cent. Both the measurement of extinction angles and the test for the index of refraction in oils, show the plagioclase to be largely andesine.[13] Quartz, which ranges considerably in amount, commonly displays strain shadows, and in some cases contains gas bubbles. Biotite rarely exceeds 10 per cent and muscovite appears in only a couple sections in small amounts.

The accessory minerals in most sections are apatite, titanite, zircon, garnet, and magnetite and show no marked changes except in one specimen which contains peculiar intergrowths (Fig. 15). The intergrowths contain a somewhat fibrous to granular aggregate of an undetermined mineral, and surround many of

[13] In an early description of a rock the same as X-218, the plagioclase was considered labradorite, having an extinction angle of 30°. Bull. 5, Ala. Geol. Surv., p. 189.

Fig. 15. Photomicrograph of a reaction rim of kelyphite formed in feldspar (light areas) around garnet in a basic gneiss. The wedge-shaped gray material adjacent to the garnet, is hornblende. The black material is magnetite. Plain light. X75.

the garnet crystals as a kelyphitic border. Cubes of magnetite, rhombs of hornblende and flakes of biotite commonly accompany the kelyphite. Besides surrounding garnet, this undetermined mineral also forms a vermicular intergrowth with plagioclase. In the same specimen, magnetite forms a vermicular structure in the hornblende and pyroxene, but it also occurs as disseminated grains. In addition to the accessories mentioned, there are grains of pyrite in two sections, and in one of these, the pyrite has encroached upon and partly replaced a small amount of pyrhotite.

Alteration products including sericite, kaolinite, hematite, limonite, leucoxene, and epidote appear in minor amounts. The iron oxides were formed as the result of alteration of magnetite. In some places hematite has entered cracks in the feldspar giving that mineral a pinkish cast. The epidote is largely scattered small grains, only a few being .7mm long. The epidote apparently formed from the alteration of hornblende or feldspar or both. A little allanite is associated with the epidote in one section.

The rocks are largely recrystallized with the grains for the most part fairly uniform in size and generally elongated with the schistosity. Other than the schistose nature resulting from recrystallization, the reaction effects (kelyphite) and undulatory extinction in quartz and feldspar, these rocks seem to have suffered no great amount of metamorphism, especially none of a cataclastic nature.

A porphyritic phase of a diorite yielded a gneiss with augen and flaser struture and a quartz-biotite groundmass. Considerable signs of cataclastic deformation are visible in this rock, being traceable from partly broken crystals to completely granulated areas. Coarse biotite flakes are lacking. The augen and flaser are composed mostly of plagioclase and a little microcline and quartz. An occasional lath of muscovite occurs in the quartz-biotite groundmass. The only accessory minerals are zircon and magnetite. The secondary products are of slight importance, iron oxides, leucoxene, kaolinite and sericite. The rounded and lenticular plagioclase crystals were probably former phenocrysts which have withstood much of the granulation which crushed the smaller crystals. The original rock was evidently a quartz diorite porphyry.

Hornblende Gneiss.

This hornblendic rock is foliated somewhat approaching a schist. It is fine-grained and dark colored, with the surface coated by iron oxide. In the thin section, hornblende comprises about one-half of the rock, and the remainder is largely quartz and andesine plagioclase with a small amount of orthoclase and microcline. The hornblende occurs as large grains between which are small grains and streaks of feldspar and quartz. Some of the twinning bands of the plagioclase show strain effects. Epidote, the only important mineral of the accessory and secondary products, is in small scattered grains in hornblende and feldspar. A few irregular grains of magnetite, traces of pyrite, some apatite, and a little limonite and leucoxene make up the rest of the rock.

Apparently this is a diorite gneiss which approaches a schist because it has undergone further metamorphism than most of the gneisses but has not been changed as far as the rock next to be described.

Hornblende Schist.

This rock is a gray-green weathered schist, fine-grained and with a 'rusted' appearance due to stains and round patches of iron oxide. The green material is hornblende which comprises about 60 per cent of the rock, with the rest chiefly feldspar (plagioclase and orthoclase) and quartz. The hornblende is somewhat replaced by biotite and iron oxide along cracks. Large irregular patches of magnetite make about 5 per cent of the rock. Some apatite and garnet are found in scattered amounts and a little kaolinite lies on some feldspar.

The rock is a hornblende schist, formed, very likely, by the metamorphism of a quartz diorite gneiss.

Miscellaneous Rocks

A few miscellaneous rocks of the group studied are of interest in that they seem to indicate the metamorphism of granite

gneisses has caused their formation. Three of these are schists and the fourth a porphyry.

Muscovite Schist.

(X-867 from Wright's Mill).

This schist contains scattered rounded and fragmental grains of quartz and feldspar and large crystals of apatite with long blades of muscovite wrapped around these minerals. Some sericite and smeared quartz together with fine grains of biotite accompany the long blades of white mica. A scattered occurrence of zircon and titanite was noted. The silicic nature and fragmental crystals suggest that the rock was formed by the further metamorphism of a granite gneiss similar to some of the gneisses found at the same locality.

Gneissic Mica Schist

X-42 NW ¼ NE ¼ Sec. 18 S., T. 19 N., R. 26 E. Yields a red micaceous soil on weathering.

The hand specimen is a weathered looking, medium-grained schistose rock. Muscovite and biotite constitute about 20 and 30 per cents respectively and occur as large, long laths. Quartz and acid plagioclase occur about as abundantly as the mica. Iron oxide stains penetrate between the crystals. Magnetite, zircon, large garnet crystals, epidote and allanite comprise the other minerals of the rock. Portions of the garnets show slight alteration to biotite, suggesting retrogressive alteration. The mineral and textural relationships indicate that this schist formed from a granite gneiss, still retaining some gneissic characters.

Weathered Micaceous Schist

X-1590 SE ¼ of NW ¼ Sec. 16, T. 19 N., R. 29 E.

This rock comes from the same vicinity as those of the group listed under "Possible Mylonites" and may represent a diaphthoritic schist, a result of retrogressive metamorphism of a granite gneiss. The specimen is heavily kaolinized and serici-

tized, with streaks and stains of iron oxide extending throughout. Large blades of muscovite, some of which feather past each other, fine flakes of biotite and finely granulated quartz together with sericite, comprise the groundmass in which lie the scattered minerals—magnetite, zircon, and tourmaline, and areas representing former lenticular feldspar crystals, now completely converted to sericite and kaolinite.

Weathered Schistose Porphyry.

X-144 Sec. 12, T. 19 N., R. 27 E., 5 miles E of Opelika, Lee Co.

This specimen is a weathered, fine-grained, somewhat schistose gray rock, containing weathered lenticular light colored crystals. The thin section is essentially fine quartzose and sericitic material, with numerous flakes of muscovite developed from the sericite. Most of the light colored lenticular crystals visible in the hand specimen, were apparently so kaolinized, or sericitized, as to be removed during the preparation of the thin section. Streaks of magnetite, minor amounts of pyrite, allanite, leucoxene, epidote, limonite, and small oval zircon grains are present.

The weathered felsic crystals suggest augen or porphyroclasts and indicate the original rock was of a porphyritic texture, probably a porphyritic granite.

Metamorphism of the Crystalline Rocks.

From the foregoing descriptions it may be seen that the crystalline rocks of the Opelika quadrangle have undergone a great amount of metamorphism during the course of their geologic history. Metamorphism appears to have occurred both in a deep zone and in a shallower zone. In the deep zone, recrystallization and neomineralization have played important roles, while in the shallow, mechanical deformation was intense and resulted in granulation and crushing of the rock constituents. Metamorphism occurred both during pre-Cambrian and during the late Paleozoic.[14] In pre-Cambrian time the Appalachian rocks

[14] Jonas, Anna I., Structure of the metamorphic belt of the southern Appalachians. Amer. Jour. Sci. vol. 24, 1932, p. 243.

were metamorphosed into crystalline schists of high rank metamorphism which were later intruded by igneous rocks ranging in composition from gabbro to granite. Belts of these high rank metamorphic schists are traceable throughout the entire length of the southern Appalachians. During the Appalachian orogeny the great overthrusting of belts of rocks subjected them to intense differential movement. Along these areas of overthrusting, crystalline schists of low rank metamorphism were formed.

In the area south of Opelika, Alabama, the Pine Mountain overthrust, a structure extending from Pine Mountain in Georgia southwest through Alabama, has produced a zone of low rank metamorphic rocks. It is in this area that the mylonites and the dense rocks occur.

Dynamic stresses acting upon granites, granodiorites, and diorites of the region recrystallized these rocks and produced new minerals (neomineralization) by the breakdown of former constituents. The same forces could have produced some of the augen, flaser, and cataclastic structures seen in various gneisses, but a large part of the deformation through granulation may have occurred later than that causing the neomineralization. Intense and rapidly applied stress is the dominant factor favoring granulation.[15] Such stresses were developed during the overthrusting of the rocks and locally caused intensive granulation, the resultant textures produced in the rocks being characteristic of deformation at shallow depths.[16]

The effects of granulation are traceable from the earliest phases of cataclastic action to the intensely deformed rock. In the beginning stages only the brittle minerals, such as quartz, are broken and cracked. Stronger deformation has produced slicing of crystals, with but slight displacement, and mortar structure in which the intergranular areas are filled by the material ground from adjacent crystals. This process, if continued, results in the smaller grains of the groundmass being broken down with only the larger crystals remaining. In the case of porphyritic rocks these crystals appear in the groundmass as rounded porphyroclasts or augen, the long axes lying perpendic-

[15] Grout, Frank F., Petrography and Petrology, p. 412.
[16] Grout, Frank F., op. cit., p. 376.

ular to the maximum pressure and roughly parallel to each other. In this latter phase schistosity is developed with the foliation around the augen and porphyroclasts. Still further crushing produces a mylonitized gneiss in which most of the original grains are granulated and somewhat streaked. This phase grades into that of a mylonite in which the mineral constituents are largely microbrecciated. We have then, evidence of intense cataclastic deformation acting on these gneisses, textures being traceable from the normal gneiss showing only traces of granulation to the thoroughly crushed mylonite.

Granulation still further than the mylonites is known to produce rocks of a much finer texture. Such a product may be analagous to the dense rocks listed under "Possible Mylonites" in this report. Crickmay[17] has traced rocks of this latter type in Georgia and has classed them as mylonites. He finds that they are formed along zones of intense movement and faulting in granite gneiss, sometimes cutting that rock much like igneous dikes. From his microscopic study, he suggests that the aphanitic texture of the groundmass of his mylonites represents extreme microbrecciation of the finer phases of the gneisses, the rounded feldspar crystals being former phenocrysts which have assumed their present shapes by rotation.

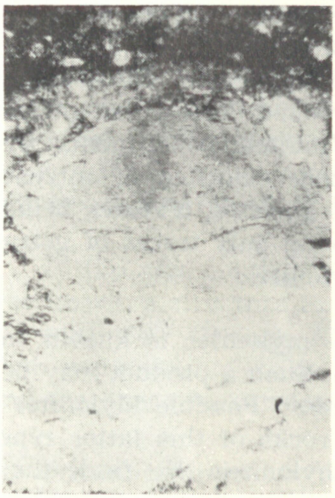
An interpretation similar to Crickmay's may be applicable to the dense rocks of this group from Alabama. In these specific rocks a gradation, such as Crickmay points out, is traceable. There are in the specimens here studied, some feldspar crystals of large size and only slightly rounded, others showing considerable rounding and fracturing, and still others with a sharply defined rounded periphery (See figs. 16, 17 & 18; also 13 & 14).

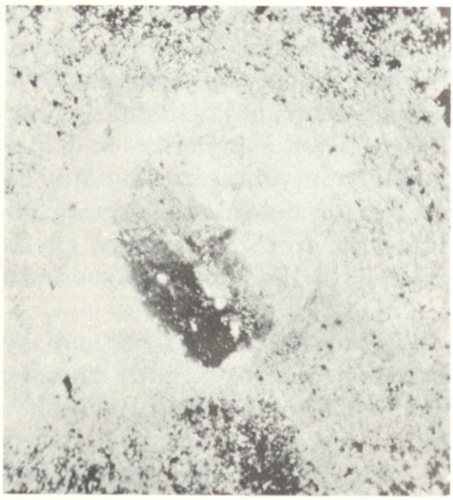
The possibility of the texture of some of these dense rocks approaching that of the pseudotachylite of Shand[18] is not to be overlooked. Hall and Molengraaff[19] have pointed out that in the

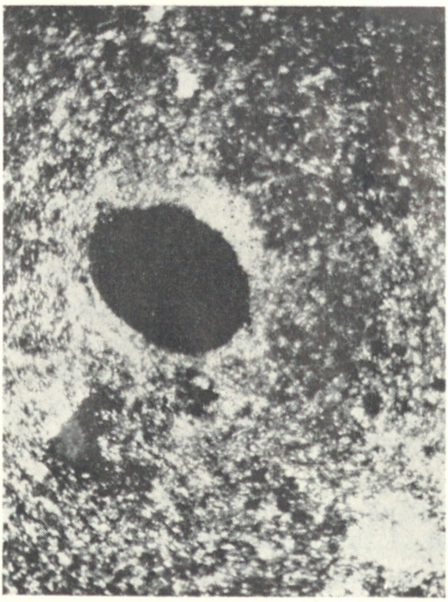
[17] Crickmay, G. W., The occurrence of mylonites in the crystalline rocks of Georgia. Manuscript (unpublished).

[18] Shand, S. J., Pseudotachylites of Parjs, Orange Free State, Geol. Soc. London, Quart. Jour. vol. 72, 1916, pp. 198-221.

[19] Hall, A. L. & G. A. F. Molengraaff, The Vredefort Mt. land in the So. Transval & No. Orange Free State. Shaler Mem. series, 1925. pp. 93-114.







Figures 16, 17 and 18 show successively what may be the rounding of phenocrysts in an ultramylonite? rock. Fig. 16 shows a large crystal of feldspar partly granulated, fig. 17 shows one which is crushed but portions of the edges partly rounded, and fig. 18 shows a feldspar with a smooth rounded periphery surrounded by a rim of sericite. Crossed nicols. X55.

flinty crush rocks in the Vredefort mountain area in the Orange Free State, heat of intense crushing has raised portions of the pulverized constituents above the fusion point, with the fused rocks solidifying into a vitreous substance, of so dense a nature, it is opaque (pseudotachylite). No evidence of fusion of this nature was noted in the Alabama material, but if these rocks were formed along zones of intense crushing conditions, phases of this type may yet be revealed.

A few of the rocks studied suggest possible retrogressive metamorphism whereby a rock which was formed in a deep zone (a katagneiss) may be changed in a shallow zone to a rock of a muscovite or chlorite schist type, the new minerals developing from those characteristic of the deep zone. This is in contrast to progressive metamorphism during which a rock of a slate type is metamorphosed to a schist and possibly ultimately to a gneiss. The alteration of garnet of a deep zone, to biotite and chlorite, is an indication of a changed environment. Some such alteration is noticeable in the garnets of a number of the Alabama rocks, but that criterion alone is not sufficient to definitely say that retrogression has occurred. The hornblende gneiss (p. 38), its schist equivalent (p. 39), and the gneissic mica schist (p. 40), are more suggestive of retrogressive action. These rocks are in a transition stage between gneisses and typical schists. A schist formed in this manner is considered by E. B. Knopf[20] to be a diaphthorite. The rocks suggesting retrogression here have a 'rusty' appearance on the outer surface such as many diaphthorites show. In the hornblende gneiss, epidote is replacing hornblende. In the gneissic mica schist there are large garnets which show biotite developed in fractures. Besides these rocks, the schists which were described may also have had a like origin, but were not 'arrested' in the transition.

Dr. Anna I. Jonas has suggested[21] that in the area of low rank metamorphism along the overthrusts in the southern Appalachians, the schists have been formed by a second metamorphism being superimposed on an earlier deep-zone one. This later metamorphic action resulted in a retrogression and a break-

[20] Knopf, Eleanora Bliss, Retrogressive metamorphism and phyllonitization. Amer. Jour. of Sci., vol. 21, 1931, pp. 1-27.

[21] Op. cit., pp. 241 & 242.

ing down of textures built up in the earlier period of deformation.

Agar[22] describes a schist from Connecticut which contains small anhedral or subhedral garnet fragments that are commonly broken or badly cracked, and have partially granulated edges. Some of these garnets show irregular replacement by fibrous biotite. This fact together with the cataclastic deformation, he considers is indicative of deep-seated retrogressive metamorphism not far advanced.

Applying the known criteria of retrogressive metamorphism to the Alabama material, it can be suggested that some such metamorphic action probably aided in the formation of at least a few of these rocks. Dr. Knopf,[23] however, cautions against affirming retrogressive metamorphism from microscopic evidence alone, for it requires a careful regional study to establish it, and it cannot as a rule be definitely determined from individual hand specimens.

Conclusion.

The pre-Cambrian rocks of the Opelika quadrangle have undergone a great deal of metamorphism during their geologic history. Original granites, granodiorites, and diorites have been subjected to dynamic stresses which caused partial or complete recrystallization and neomineralization of the rocks. During the Appalachian orogeny, great belts of already metamorphosed rocks were subjected to folding and overthrusting. This resulted in intensive granulation and crushing along certain zones within the gneisses, so that mylonite gneiss, mylonites, and rocks resembling ultramylonites were produced. Successive stages can be traced from a partly granulated rock to those in which microbrecciation has been so extensive that only remnants of the larger grains remain scattered in the finely pulverized groundmass. Besides the cataclastic deformation, there are indications of retrogressive metamorphism in a number of the rocks, especially in schists which have formed from the gneisses.

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[22] Agar, Wm. M., Petrology and structure of the Salisbury-Canaan district of Conn. Amer. Jour. Sci., vol. 23, 1932, pp. 31-49.

[23] Op. cit., p. 27.

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